Can the Minimal Supersymmetric Standard Model with Light Bottom Squark and Light Gluino Survive Z-Peak Constraints?

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In the framework of the minimal supersymmetric model we examine the Z-peak constraints on the scenario of one light bottom squark (sbottom) ($\sim 2-5.5$ GeV) and light gluino ($\sim 12-16$ GeV), which has been successfully used to explain the excess of bottom quark production in hadron collisions. Such a scenario is found to be severely constrained by the CERN LEP Z-peak observables, especially by R_b, due to the large effect of gluino-sbottom loops. To account for the R_b data in this scenario, the other mass eigenstate of sbottom, i.e., the heavier one, must be lighter than 125 (195) GeV at $2\sigma(3\sigma)$ level, which, however, is disfavored by CERN LEP II experiments.

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Introduction.—Although the standard model (SM) has been successful phenomenologically, it is generally believed to be an effective theory valid at the electroweak (EW) scale, and some new physics must exist beyond the SM. This belief was seemingly corroborated by some experiments, such as the recent measurement of muon $g-2$ [1] and the evidence of neutrino oscillations [2]. Among various speculations of new physics theories, the minimal supersymmetric model (MSSM) is arguably a promising candidate and has been intensively studied in the past decades.

The nonobservation of any sparticles from direct experimental searches suggested heavy masses for the sparticle spectrum. However, there have been a lot of analyses [3] which argue that a very light bottom squark (sbottom) and light gluino (with mass of a few GeV) may have escaped from the direct experimental searches. It is intriguing that a light sbottom may require a light gluino, as analyzed in the last reference in [3]. A recent analysis [4] showed that a light sbottom ($\tilde{b}_1$) with mass comparable to the bottom quark is still allowed by electroweak precision data if its coupling to the Z boson is small enough. A study by Berger *et al.* [5] found that the scenario of MSSM with one light sbottom ($\sim 2-5.5$ GeV) and a light gluino ($\sim 12-16$ GeV) can successfully provide an explanation for the long-standing puzzle that the measured cross section of bottom quark production at the hadron collider exceeds the QCD prediction by about a factor of 2 [6]. They also argued that such a scenario is consistent with all experimental constraints on the masses and couplings of sparticles.

We note that the previous examinations [4] on Z-peak constraints focused on the direct production of a light sbottom followed by its decay similar to the bottom quark. Then by fine-tuning the mixing of left- and right-handed sbottoms, the coupling of the Z boson to the lighter mass eigenstate of sbottom ($\tilde{b}_1$) can be sufficiently small so as to avoid the Z-peak constraints. It is noticeable that when the sbottom $\tilde{b}_1$ and gluino are both light, as was used to explain the excess of bottom quark production in hadron collision [5], gluino-sbottom loops may cause large effects in $Zb\bar{b}$ coupling. [Previous calculations of supersymmetric (SUSY) loop effects on $Zb\bar{b}$ coupling focused on rather heavy squarks and gluinos and thus obtained very small effects [7].] Therefore, in such a scenario, it is important to reexamine the loop contributions to $Zb\bar{b}$ coupling and, further, the Z-peak constraints. This is the aim of this Letter. Through explicit calculations, we find that gluino-sbottom loops comprising of sbottoms and a light gluino cause large effects on Z-peak observables. To account for the R_b data, subtle cancellation between $\tilde{b}_1$ loops and $\tilde{b}_2$ loops is needed, which can be realized by requiring that the mass splitting between two sbottoms not be too large. Numerical results show that for $\tilde{b}_1$ with a mass of $\sim 2-5.5$ GeV, $\tilde{b}_2$ must be lighter than 125 and 195 GeV at 2σ and 3σ levels, respectively.

Calculations.—We start the calculations by writing down the sbottom mass-square matrix [8]

$$M_{\tilde{b}}^2 = \begin{pmatrix} M_{\tilde{b}_{LL}}^2 & M_{\tilde{b}_{LR}}^{2\dagger} \\ M_{\tilde{b}_{LR}}^2 & M_{\tilde{b}_{RR}} \end{pmatrix}, \quad (1)$$

where $M_{\tilde{b}_{LL}}^2 = M_{\tilde{Q}}^2 + m_b^2 - m_Z^2(\frac{1}{2} - \frac{1}{3}\sin^2\theta_W)\cos(2\beta)$, $M_{\tilde{b}_{RR}}^2 = M_{\tilde{D}}^2 + m_b^2 - \frac{1}{3}m_Z^2\sin^2\theta_W\cos(2\beta)$, and $M_{\tilde{b}_{LR}}^2 = m_b(A_b - \mu\tan\beta)$. Here $M_{\tilde{Q}}^2$ and $M_{\tilde{D}}^2$ are soft-breaking mass terms for left-handed squark doublets $\tilde{Q}$ and right-handed down squarks, respectively. A_b is the coefficient of the trilinear term $H_1\tilde{Q}\tilde{D}$ in soft-breaking terms and $\tan\beta = v_2/v_1$ is the ratio of the vacuum expectation values of the two Higgs doublets. By diagonalizing the sbottom mass-square matrix, one obtains the physical mass eigenstates $\tilde{b}_{1,2}$,

$$\begin{pmatrix} \tilde{b}_1 \\ \tilde{b}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{b}_L \\ \tilde{b}_R \end{pmatrix}, \quad (2)$$

where θ is the mixing angle of sbottoms. In our following analyses we take the sbottom masses and the mixing angle as free parameters since they are independent of each other and determined by SUSY parameters $M^2_{\tilde{b}_{LL}}$, $M^2_{\tilde{b}_{RR}}$, and $M^2_{\tilde{b}_{LR}}$.

The coupling of Z bosons to sbottoms is given by

$$V^{\mu}(Z\tilde{b}_i\tilde{b}_j^*) = ieO_{ij}(p_1 + p_2)^{\mu}, \qquad (3)$$

where $p^{\mu}_{1,2}$ are the momentum of $\tilde{b}_i$ and $\tilde{b}_j$. O_{ij} are defined as $O_{11} = v_b + a_b\cos 2\theta$, $O_{22} = v_b - a_b\cos 2\theta$, and $O_{12} = O_{21} = -a_b\sin 2\theta$. Here $v_b = 1/(4\sin\theta_W\cos\theta_W)(1 - \frac{4}{3}\sin^2\theta_W)$ and $a_b = 1/(4\sin\theta_W\cos\theta_W)$ are the vector and axial vector couplings of $Zb\bar{b}$, respectively.

Apparently, a light sbottom $\tilde{b}_1$ (a few GeV) can affect Z-peak observables in two ways: (i) the direct pair production of $\tilde{b}_1$ through $Z\tilde{b}_1\tilde{b}_1^*$ coupling, as discussed in [4]; (ii) the loop effects of $\tilde{b}_1$. If the gluino is also light (~12–16 GeV), then the loop effects are mainly from gluino-sbottom loops in the $Zb\bar{b}$ vertex, which comprise a light gluino $\tilde{g}$ and sbottoms, as shown in Fig. 1. It should be noted that, even if the direct pair production of $\tilde{b}_1$ is avoided by tuning the mixing angle $|\cos\theta| \simeq \sqrt{2/3}\sin\theta_W \simeq 0.38$ to set $Z\tilde{b}_1\tilde{b}_1^*$ coupling to be zero ($O_{11} \sim 0$), $Z\tilde{b}_1\tilde{b}_2^*$ and $Z\tilde{b}_2\tilde{b}_2^*$ couplings still exist, and the irreducible loops shown in Fig. 1(b) make contributions. It should also be noted that the self-energy loops in Fig. 1(a) involve only SUSY QCD interactions, i.e., gluino-sbottom-bottom couplings, which are not affected by the zero $Z\tilde{b}_1\tilde{b}_1^*$ coupling.

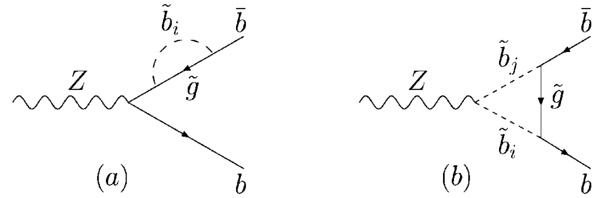

FIG. 1. The gluino one-loop diagrams for $Zb\bar{b}$.

Using dimensional regulation and adopting the on-shell renormalization scheme for the calculation of Fig. 1, we obtain the effective $Zb\bar{b}$ vertex

$$V^{\text{eff}}_{\mu}(Zb\bar{b}) = ie\left\{\gamma_{\mu}(v_b - a_b\gamma_5) + \frac{\alpha_s}{3\pi}[F_1\gamma_{\mu} + F_2\gamma_{\mu}\gamma_5 + iF_3\sigma_{\mu\nu}k^{\nu} + iF_4\sigma_{\mu\nu}k^{\nu}\gamma_5]\right\}. \qquad (4)$$

Here F_i are form factors originated from loop corrections, given by

$$F_1 = 2\sum_{i,j=1}^{2} O_{ij}\{-A^-_{ij}m_bm_{\tilde{g}}[C_0(i,j) + C_{11}(i,j)] + A^+_{ij}[m_b^2[C_{11}(i,j) + C_{21}(i,j)] + C_{24}(i,j)]\} + v_b\delta Z_V + a_b\delta Z_A, \qquad (5)$$

$$F_2 = 2\sum_{i,j=1}^{2} O_{ij}B^+_{ij}C_{24}(i,j) - v_b\delta Z_A - a_b\delta Z_V, \qquad (6)$$

$$F_3 = -\sum_{i,j=1}^{2} O_{ij}\{A^+_{ij}m_b[C_{11}(i,j) + C_{21}(i,j)] - m_{\tilde{g}}A^-_{ij}[C_0(i,j) + C_{11}(i,j)]\}, \qquad (7)$$

$$F_4 = \sum_{i,j=1}^{2} O_{ij}\{B^+_{ij}m_b[2C_{12}(i,j) - C_{11}(i,j) - C_{21}(i,j) + 2C_{23}(i,j)] + m_{\tilde{g}}B^-_{ij}[C_0(i,j) + C_{11}(i,j)]\}, \qquad (8)$$

where

$$\delta Z_V = \sum_{i=1}^{2}\left[A^+_{ii}\left(B_1(i) + 2m_b^2\frac{\partial B_1(i)}{\partial p_b^2}\right) - 2m_bm_{\tilde{g}}A^-_{ii}\frac{\partial B_0(i)}{\partial p_1^2}\right]\Bigg|_{p_b^2=m_b^2}, \qquad (9)$$

$$\delta Z_A = -\sum_{i=1}^{2} B^+_{ii}B_1(i). \qquad (10)$$

Here $B_{0,1}(j) = B_{0,1}(-p_b, k, m_{\tilde{g}}, m_{\tilde{b}_j})$ and $C_{0,nm} = C_{0,nm}(-p_b, k, m_{\tilde{g}}, m_{\tilde{b}_i}, m_{\tilde{b}_j})$, with p_b and k denoting the four momentum of the b quark and Z boson, respectively, are the Feynman loop integral functions and their expressions can be found in [9]. Other constants appearing above are defined by $A^{\pm}_{ij} = a_ia_j \pm b_ib_j$, $B^{\pm}_{ij} = a_ib_j \pm a_jb_i$, $a_{1,2} = (\sin\theta \mp \cos\theta)/\sqrt{2}$, and $b_{1,2} = (\cos\theta \pm \sin\theta)/\sqrt{2}$.

Numerical results.—Let us now evaluate the effects of the above corrections to Z-peak observables. We start with $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$. From Eq. (4) we obtain the contribution to R_b,

$$\delta R_b = R_b^{\text{SM}}(1 - R_b^{\text{SM}})\Delta_{\text{SUSY}}, \qquad (11)$$

where

$$\Delta_{\text{SUSY}} = \frac{2\alpha_s}{3\pi}\frac{1}{v_b^2(3 - \beta^2) + 2a_b^2\beta^2} \times [v_b(3 - \beta^2)\,\text{Re}F_1 - 2a_b\beta^2\,\text{Re}F_3 + 6m_bv_b\,\text{Re}F_4] \qquad (12)$$

with $\beta = \sqrt{1 - 4m_b^2/m_Z^2}$.

To obtain numerical results, we set input parameters as [10] $R_b^{\text{exp}} = 0.21642 \pm 0.00065$, $R_b^{\text{SM}} = 0.21573 \pm 0.0002$, $\sin^2\theta_W = 0.2312$, $\alpha_s(m_Z) = 0.1192$, $m_Z = 91.188$ GeV, and $m_b = 4.75$ GeV. We will vary $m_{\tilde{g}}$ in the range ~12–16 GeV and $m_{\tilde{b}_1}$ in the range ~2–5.5 GeV as was used in [5].

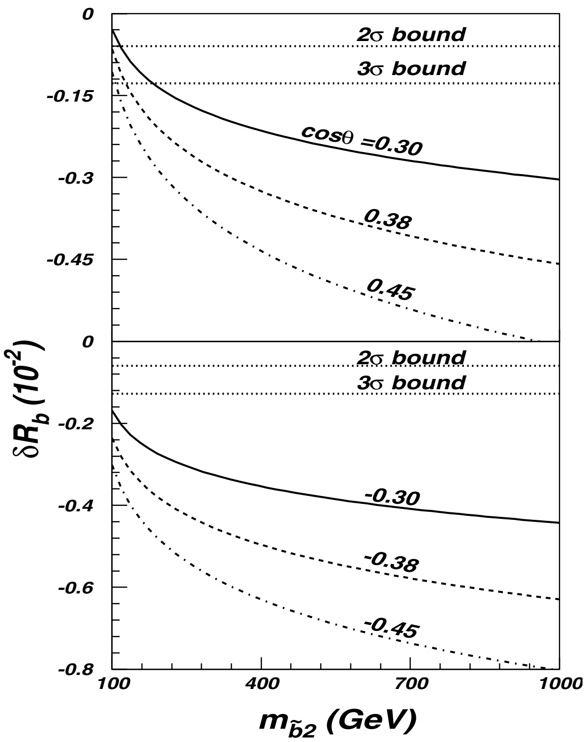

FIG. 2. δR_b as a function of $m_{\tilde{b}_2}$ for $m_{\tilde{b}_1} = 3.5$ GeV and $m_{\tilde{g}} = 14$ GeV. The corresponding region above each horizontal line is allowed by CERN LEP R_b data at 2σ and 3σ levels, respectively.

For $m_{\tilde{b}_1} = 3.5$ GeV and $m_{\tilde{g}} = 14$ GeV, we present δR_b versus $m_{\tilde{b}_2}$ in Fig. 2. In addition to $\cos\theta = \pm 0.38$ which leads to zero $Z\tilde{b}_1\tilde{b}_1^*$ coupling and hence avoids the large rate of direct pair production of $\tilde{b}_1$ [4], we also plotted the curves for $\cos\theta = \pm 0.30$ and ± 0.45. From the figure, one sees that the contributions to R_b are negative in all the parameter space we have investigated. One can also see that the negative $\cos\theta$ gives larger contributions than positive one and as $|\cos\theta|$ increases, the contributions become more sizable.

Comparing with the experimental bounds shown in Fig. 2, one learns that even in the favorable case of positive $\cos\theta$, the contribution to R_b is too large to be allowed at the 3σ level if $m_{\tilde{b}_2} \geq 200$ GeV. Since the heavier sbottom has not been observed at CERN LEP II, and it can, in principle, be produced in association with the lighter one, its mass should be larger than about 200 GeV. (A detailed study may be needed to make this bound quantitative.) So, we conclude that the scenario of one light sbottom and light gluino faces severe challenge. As to the largeness of the gluino-sbottom loop contributions, two main reasons may account for it. One is the large splitting between $m_{\tilde{b}_1}$ and $m_{\tilde{b}_2}$, which leads to a weak cancellation between $\tilde{b}_1$ and $\tilde{b}_2$ contributions; the other is the lightness of the sbottom $\tilde{b}_1$ and the gluino, which induces large self-energy contributions. To check our understanding, we fix $m_{\tilde{b}_2}$ and $m_{\tilde{g}}$ but let $m_{\tilde{b}_1}$ approach $m_{\tilde{b}_2}$. Then we do find that large cancellation occurs between different diagrams.

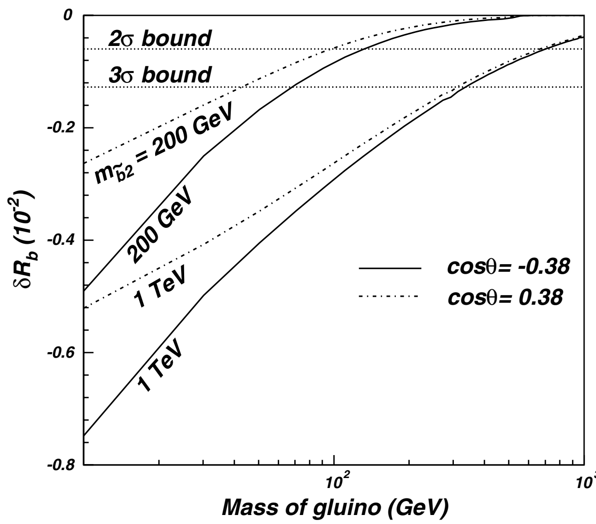

FIG. 3. Same as Fig. 2, but versus gluino mass for $m_{\tilde{b}_1} = 3.5$ GeV.

We notice from Fig. 2 the intriguing feature that, as $m_{\tilde{b}_2}$ increases, the effects become more sizable. This can be understood as the weaker cancellation between $\tilde{b}_1$ and $\tilde{b}_2$ contributions when $m_{\tilde{b}_2}$ increases. To further understand this behavior, we used approximate forms of B and C functions [9], and found that, in the limit $m_{\tilde{b}_2}^2 \gg m_Z^2 > m_{\tilde{b}_1,\tilde{g}}^2$, δR_b is roughly linear dependent on $\ln(m_{\tilde{b}_2^2}/m_{\tilde{b}_1^2})$ and thus increases as $m_{\tilde{b}_2^2}/m_{\tilde{b}_1^2}$ gets larger. Of course, this feature does not mean that SUSY QCD is nondecoupling from the SM. To check the decoupling property of SUSY QCD, we let all relevant sparticles $(\tilde{b}_1, \tilde{b}_2, \tilde{g})$ become heavy and found that the contributions drop quickly to zero. Actually, even for a light $\tilde{b}_1$, δR_b drops monotonously to zero when $m_{\tilde{g}}$ becomes large, as shown in Fig. 3.

Since in such a scenario, with a light $\tilde{b}_1$ of a few GeV, the $\tilde{b}_2$ lighter than 200 GeV is disfavored by the CERN LEP II experiment [4], we fix $m_{\tilde{b}_2} = 200$ GeV and $\cos\theta = 0.3$

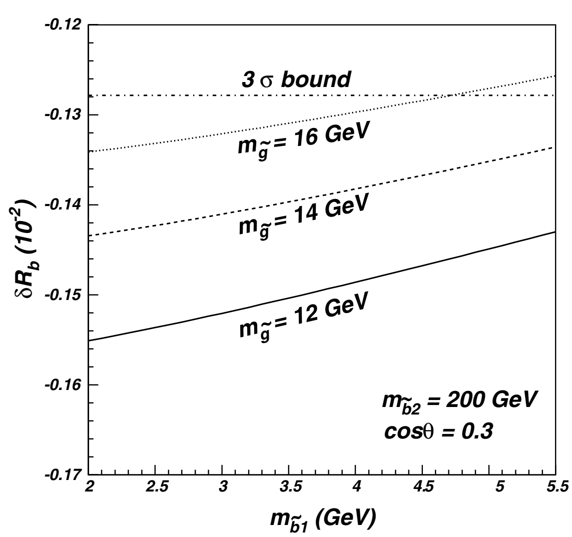

FIG. 4. Same as Fig. 2, but versus $m_{\tilde{b}_1}$ for $m_{\tilde{b}_2} = 200$ GeV.

TABLE I. Deviation of some Z-peak observables from experimental values. The MSSM predictions are obtained by including SUSY QCD contributions with $m_{\tilde{b}_1} = 3.5$ GeV and $m_{\tilde{g}} = 14$ GeV. The SM predictions are taken from [11]. The values of $m_{\tilde{b}_1}$ are in units of GeV.

	MSSM						
	$\cos\theta = 0.30$			$\cos\theta = 0.45$			
	$m_{\tilde{b}_2}$						
	150	200	250	150	200	250	SM
R_b	2.66σ	3.22σ	3.59σ	4.49σ	5.47σ	6.16σ	1.12σ
R_c	-0.19σ	-0.22σ	-0.24σ	0.28σ	-0.33σ	-0.36σ	-0.12σ
R_ℓ	2.26σ	2.66σ	2.93σ	3.65σ	4.32σ	4.83σ	1.11σ
A_b	-0.90σ	-0.93σ	-0.94σ	-0.76σ	-0.80σ	-0.84σ	-0.64σ
A_{FB}^b	-3.25σ	-3.28σ	-3.30σ	3.06σ	-3.12σ	-3.16σ	-2.90σ

and plot δR_b versus $m_{\tilde{b}_1}$ in Fig. 4, where $m_{\tilde{b}_1}$ varies in the range $\sim$2–5.5 GeV and $m_{\tilde{g}}$ varies in $\sim$12–16 GeV, as used in [5] to explain the excess of bottom quark production in hadron collision. We see that such a scenario is totally excluded by the CERN LEP R_b data at the 2σ level, while at the 3σ level only a tiny corner with $m_{\tilde{g}}$ close to 16 GeV and $m_{\tilde{b}_1}$ close to 5 GeV is allowed.

Let us next consider the effects on other Z-peak observables: R_c, R_ℓ, A_b, and A_{FB}^b. In our calculation of these observables, we neglect the SUSY QCD correction to $\Gamma(Z \to q\bar{q})$ $(q \neq b)$ since the corresponding loops involve squarks $\tilde{q}$ $(\tilde{q} \neq \tilde{b})$ which are assumed to be heavy. Then the effects on all these observables stem only from the corrections to the $Zb\bar{b}$ vertex in Eq. (4). Since $F_{1,2}$ are found to be much larger than $F_{3,4}$, we neglect $F_{3,4}$ in the calculation of A_b and A_{FB}^b. In Table I, we show the effects on these observables, including R_b. We see that gluino-sbottom loop effects significantly enlarge the deviations of the predictions from the experimental values.

We should recall that in the calculation we considered only the SUSY QCD loops, i.e., gluino-sbottom loops. Since we focused on a special scenario of the MSSM, in which there exist a very light sbottom ($\sim$2–5.5 GeV) and a very light gluino ($\sim$12–16 GeV), such gluino-sbottom loop effects are much larger than SUSY electroweak corrections [7]. In fact, we recalculated SUSY EW corrections to R_b and found they are indeed small under the current experimental limits on the masses of charginos and stops. The dominant contributions from chargino loops are found to be positive (opposite from SUSY QCD corrections) and at the level of 10^{-4}, which is about 1 order smaller than our present SUSY QCD corrections.

Conclusions.—From the above analyses we conclude that the scenario of the MSSM with one light sbottom ($\sim$2–5.5 GeV) and light gluino ($\sim$12–16 GeV) can give rise to large effects on the $Zb\bar{b}$ vertex through gluino-sbottom loops. Such effects significantly enlarge the deviations of some Z-peak observables, especially R_b, from their experimental data. To account for the R_b data in this scenario, the other mass eigenstate of sbottom, i.e., the heavier one, must be lighter than 125 (195) GeV at $2\sigma(3\sigma)$ level, which, however, is disfavored by CERN LEP II experiments.

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